PLANAR OPTICAL IMAGE SENSOR AND SYSTEM FOR GENERATING AN ELECTRONIC IMAGE OF A RELIEF OBJECT FOR FINGERPRINT READING

Background of the Invention

Field of the Invention

The invention relates to an optical sensor system. More particularly, the invention relates to an optical sensor, system and method of detecting a presence of a relief object, such as a fingertip, and generating an electronic image of the relief object.

Description of the Related Art

Optical sensor systems are often configured to include an optical sensor in communication with peripheral control and drive circuits. In one application, the optical sensor system is part of a facsimile machine and optical sensors convert a written document into an electronic signal which is transmitted over a communications system to a remote receiving facsimile device. In another application, an optical sensor generates an electronic representation or image of a relief object. The relief object can be the tip of a finger which causes a fingerprint when placed on a surface. When the optical sensor generates an electronic representation of the fingerprint, the optical sensor may be referred to as a fingerprint sensor.

A fingerprint sensor is an example of a biometric device that uses a human characteristic to identify a user. Fingerprint sensors are commonly installed in access-restricted locations where high-level security is needed. They may also be connected to a computer to allow access and operation of the computer only after the user has been identified as an authorized user.

It is important that fingerprint sensors used to identify persons and to allow authorized users access to computers and restricted areas, be reliable. It is also

advantageous that such sensors equally recognize wet, oily and dry fingers. In addition, fingerprint sensors should have surfaces that resist wear and allow easy cleaning.

Summary of the Invention

The present invention comprises an improved optical sensor for detecting a presence of a relief object and for generating an electronic representation of the relief object. The relief object may be a structured-surface object such as a fingertip or a plain-surface object such as a pointer.

An aspect of the invention generally involves an optical module onto which a user can place a fingertip. The surface of the fingertip has a structure or pattern of ridges and valleys that represent a fingerprint. In operation, the user places the fingertip on the optical module and the optical module illuminates the surface of the fingertip. Inclined walls of the valleys reflect light back into the optical module where the reflected light is incident on photosensitive elements located underneath the valleys. In contrast to the valleys, the ridges cover underlying photosensitive elements and no light reaches these covered photosensitive elements. Every illuminated photosensitive element outputs a HIGH signal indicating that a valley is located above the photosensitive element. Non-illuminated photosensitive elements output only LOW signals. The entirety of the HIGH and LOW signals represent a digital image of the fingerprint for further processing.

Another aspect of the invention involves a fingerprint sensor. The fingerprint sensor includes a transparent material having a contact surface which receives a fingertip of a user. A source of optical radiation is disposed on one side of the transparent material and directs the radiation through the transparent material for reflection by the fingertip. Detectors are disposed on one side of the transparent material and positioned to receive radiation reflected by the fingertip. The detectors generate electrical signals in response to the detected radiation.

A further aspect of the invention involves an optical image sensor system. The system includes an optical module and a driver module connectable to a

controller. The system further includes a power supply connectable to the controller. The optical module is connected to the driver module and comprises a transparent material having a contact surface which receives a fingertip of a user. A source of optical radiation is disposed on one side of the transparent material and directs the radiation through the transparent material for reflection by the fingertip. Detectors are disposed on one side of the transparent material and positioned to receive radiation reflected by the fingertip. The detectors generate electrical signals in response to the detected radiation.

A further aspect of the invention involves a method of generating an electronic representation of a relief object. The relief object is placed on a surface of an optical module and light is passed through the surface of the optical module to illuminate the relief object from within the optical module. Photosensitive elements of the optical module are operated in a detect mode which detects light reflected from the relief object. The reflected light causes a photocurrent in each illuminated photosensitive element. Each photocurrent acts on a charge-storing mechanism assigned to a photosensitive element. The photosensitive elements are operated in a read mode associated with the charge-storing mechanism to determine if a photosensitive element has been exposed to light during the detect mode.

Another aspect of the invention involves a method of detecting a fingertip. A user places a finger in contact with a surface of a material transparent to optical radiation such that the finger contacts the surface over a surface area. Optical radiation is passed through the transparent material to illuminate the surface area. The finger reflects the optical radiation to provide reflected optical radiation. The reflected optical radiation is used to illuminate photosensitive elements by passing the reflected optical radiation through the transparent material.

A further aspect of the invention involves a fingerprint sensor that comprises a transparent material, a source of optical radiation, and detectors. The transparent material has a surface which receives a fingertip of a user. The source of optical radiation is disposed on one side of the transparent material and directs the radiation

through the transparent material for reflection by the fingertip. The detectors are disposed on one side of the transparent material and positioned to receive radiation reflected by the finger. The detectors generate electrical signals in response to the detected radiation, and a circuit converts the electrical signals into an electronic representation of a fingerprint.

Another aspect of the invention involves an optical sensor. The optical sensor comprises a transparent material, a source of optical radiation, and a detector. The transparent material has a surface which receives a fingertip of a user. The source of optical radiation is disposed on one side of the transparent material and directs the radiation through the transparent material for reflection by the fingertip. The source being substantially planar and having an emitting area that is approximately the same size as the surface of the transparent material. The detector is disposed on the one side of the transparent material and positioned to receive radiation reflected by the fingertip. The detector generates electrical signals in response to the detected radiation.

A further aspect of the invention involves an optical sensor. The optical sensor includes a transparent material, a source of optical radiation, and a detector. The transparent material has a surface which receives a fingertip of a user. The source of optical radiation is disposed on one side of the transparent material and directs the radiation through the transparent material for reflection by the fingertip. The detector is disposed on the one side of the transparent material and positioned to receive radiation reflected by the fingertip. The detector comprises an array of photosensitive elements positioned between the source and the transparent material and generates electrical signals in response to the detected radiation. A circuit processes the detected signals.

An additional aspect of the invention involves a sensor. The sensor comprises a transparent material and a planar array of pixels on one side of the transparent material. The transparent material has a surface which receives an object. Each pixel includes a source of optical radiation and a photosensitive element. The source is configured to

direct the radiation through the transparent material for reflection by the object, and the detector is configured to generate an electrical signal in response to incident radiation.

A further aspect of the invention involves a fingerprint sensor that includes a transparent material having a surface which receives a fingerprint of a user. At least one light source illuminates the surface for reflection by the fingerprint, and a collector is positioned to collect light reflected from the user's fingerprint. A detector receives light collected by the collector; wherein said at least one light source is arranged so that light directed towards valleys of the fingerprint is collected by the collector, while light directed towards ridges of the fingerprint is not collected by the collector.

For purposes of summarizing the invention, certain aspects, advantages and novel features of the invention have been described herein. Of course, it is to be understood that not necessarily all such aspects, advantages or features will be embodied in any particular embodiment of the invention.

Brief Description of the Drawings

These and other aspects, advantages, and novel features of the invention will become apparent upon reading the following detailed description and upon reference to the accompanying drawings. In the drawings, same elements have the same reference numerals.

Figure 1 shows an overview of an optical image sensor system.

Figure 2 shows an embodiment of an optical module.

(1) Figure 3A shows a side view of a first embodiment of an optical module.

(2) Figure 3B shows a side view of a second embodiment of an optical module.

(3) Figure 4 shows a side view of a third embodiment of an optical module.

Figure 5 shows upper layers of an optical module with a fingertip placed on a top surface.

Figure 6 shows a section of the upper layers shown in Figure 5 with a ridge of a fingertip covering a photosensitive pixel.

Figure 7 shows a section of the upper layers shown in Figure 5 with a valley of a fingertip located above a photosensitive pixel.

Figure 8 shows a schematic circuit diagram of a matrix of photosensitive pixels comprising diodes.

Figures 8A and 8B show timing diagrams of address and detector voltages.

Figure 9 shows a schematic circuit diagram of a matrix of photosensitive pixels comprising transistors.

Figures 10A-10D show timing diagrams illustrating operation of the circuit shown in Figure 9.

Figure 11 shows an embodiment of fingerprint sensing system.

Figure 12 shows a flow chart of a read-out procedure.

Figure 13 shows a blockdiagram of a driver module.

Figure 14 shows an embodiment of an optical module having photodetectors and light sources located within one layer.

(5) Figure 15 shows a first embodiment of a photodetector of a pixel.

(6) Figure 15A shows a second embodiment of a photodetector of a pixel.

Figure 16 shows an exemplary topography of a pixel layout.

(7) Figure 17 shows an embodiment of an optical module that comprises an optical lens.

Figure 17A shows an embodiment of a light source of a pixel.

(8) Figure 18 shows a first embodiment of a light source.

(9) Figure 19 shows a second embodiment of a light source.

(10) Figure 20 shows an embodiment of an optical module that comprises a reflector and an optical lens.

(11) Figure 21 shows a further embodiment of an optical module.

(12) Figure 22 shows an embodiment of an optical module that comprises a fiber optic bundle.

Detailed Description of the Preferred Embodiment

Figure 1 shows an exemplary embodiment of an optical image sensor system 3. The optical image sensor system 3 generates an electronic signal in response to an object that is placed on an optical module 1. The electronic signal may indicate

the presence of the object or correspond to an electronic representation of a surface of the object. In one embodiment, the object is a pencil-like pointer used, for example, to select an icon on a touch pad or "write" on the touch pad. In another embodiment, the object is a relief object such as a tip of a person's finger. As is well known, a human fingertip has a surface that forms a unique pattern of ridges and valleys. The structure of the fingertip, or a print caused when the fingertip is placed on a surface is often referred to as a "fingerprint." Hereinafter, this term is generally used to refer to the print caused by the fingertip.

Embodiments of the invention are described with reference, but not limited, to a fingertip as the object placed upon the optical module 1. In response to the presence of the fingerprint, the optical module 1 generates in one embodiment the electronic representation ("electronic image" or "digital image") of the fingerprint. The fingerprint resulting from the sensing of the physical fingerprint of the user is referred to as the "sensed" fingerprint to distinguish it from a "stored" fingerprint of an authorized user. As described below in greater detail, if the sensed fingerprint matches the stored fingerprint, the present user is identified as the authorized user.

The illustrated optical image sensor system 3 further includes a power supply 4, a driver module 2 and a controller 6. A connection L1 connects the power supply 4 to the optical module 1, and a connection L2 connects the driver module 2 to the optical module 1. The controller 6 is connected to the driver module 2 and the power supply 4 through connections L3, L4, respectively. A connection L5 connects the controller 6, for example, to a processor unit of a host system (not shown).

The host system may be a personal computer (PC), a laptop computer, a cellular phone, a security system, or other equipment installed, for example, in an access-restricted location where high-level security is needed. The host system processes the sensed fingerprint of the present user and matches it with the stored fingerprint of the authorized user. The host system allows full operation of the host

system itself, or access to the restricted areas only if the electronic representation of the sensed fingerprint matches the stored fingerprint of the authorized user.

In one embodiment, the optical image sensor system 3 is an external apparatus that is connectable to a computer (e.g., a desktop computer or a laptop). The computer includes a software program that operates the computer and the optical image sensor system 3 and performs a matching procedure. In other embodiments, the optical image sensor system 3 may be implemented, for example, within a computer or a cellular phone. In these embodiments, the optical module 1 is located so that a user may place a finger on an exposed surface of the optical module 1. For instance, the optical module may be integrated into a keyboard of a computer or next to the keypad of a cellular phone. Remaining components of the optical image sensor system 3 are then located within the computer or the cellular phone.

In alternative embodiments the optical image sensor system 3 may be implemented as a portable, autonomous identification and/or authentication apparatus that includes the components and software to perform the matching procedure and to output the result of the matching procedure. For example, the optical image sensor system 3 may be implemented within a smart or chip card, or a communications module designed in accordance with a specification defined by the Personal Computer Memory Card International Association (PCMCIA). The communications module is, thus, often referred to as a PCMCIA card.

Focusing on an exemplary embodiment of the optical module 1, Figure 2 shows a perspective view of the optical module 1 to illustrate a general structure of the optical module 1. In one embodiment, the optical module 1 includes multiple layers and has a flat, generally rectangular shape with a planar top surface 15. The optical module 1 may have a thickness of about 1-2 mm, a length of about 3 cm, and a width of about 2 cm. The top surface 15 forms an exposed contact area onto which the user places a finger. The contact area is, for example, about 6 cm^2. In other

embodiments, the top surface 15 may have a circular-, oval-, square-like, or any other shape of sufficient size to contact a sufficiently large part of the finger.

Figure 2, as well as the other figures, illustrates the optical module 1 so that the top surface 15 and the contact area are horizontal. Terms, such as "top," "bottom," "above," "below," "underneath," or the like, to describe the orientation of an element or a layer of the optical module 1 are, thus, used with reference to the horizontal orientation of the optical module 1. Those skilled in the art will appreciate that the optical module 1 may have another orientation and that the terms then apply correspondingly.

From top to bottom, the optical module 1 has a detector layer 10, a substrate layer 8, and a light source layer 12. It is contemplated that, in another embodiment, the optical module 1 may include additional layers (e.g., a surface coating) as shown in Figure 3. The detector layer 10 includes a plurality of individual, spaced-apart photosensitive areas. Each photosensitive area is a pixel 14 of an optical array with the pixels 14 being arranged in M rows and N columns. In one embodiment, the pixel 14 has M = 315 rows and N = 240 columns. As described below with reference to Figure 5, each pixel 14 includes in one embodiment a photodetector 24 and a charge-storing mechanism, for example, an inherent (parasitic) capacitance or a capacitor 26 electrically coupled to the photodetector 24. Each pixel 14, hence, each photodetector 24, can be selected through an address line L_M (row) and a data line L_N (column). To illustrate the array structure of the detector layer 10, the address lines L_M and the data lines L_N are indicated in the detector layer 10, but it is contemplated that these lines are for illustrative purposes only and typically not visible. The address lines L_M and the data lines L_N are connected to the connection L2 that connects the optical module 1 to the driver module 2.

plurality

pixels

The photosensitive areas are implemented on top of the substrate layer 8 which is transparent for light emitted by the light source layer 12. For instance, the photosensitive areas may be deposited directly on the substrate layer 8. In one embodiment, a rigid substrate such as glass forms the substrate layer 8. The glass

substrate may have a thickness of about 1 mm. Other suitable, transparent materials include plastic-like materials.

In the illustrated embodiment, the light source layer 12 is in direct contact with the substrate layer 8, and connected to the power supply 4 which provides electrical power for the light source layer 12. The light source layer 12 includes a single light source that extends across the glass substrate and illuminates the glass substrate evenly. In other embodiments, the light source layer 12 may include multiple individual light sources located to evenly cover and illuminate the glass substrate, an array emitter including pixelized light sources, or a light source panel such as an electroluminescent panel. The term "light source" is therefore intended to encompass single or multiple light sources or light source panels which may have a variety of configurations. When the light source is activated, light propagates in upward direction through the transparent substrate layer 8 and the detector layer 10 to illuminate the top surface 15. The light source, therefore, functions as a backlight for the top surface 15 of the optical module 1.

The light source layer 12, and thus the light source, may therefore be implemented in a variety of different ways. The light source may be an electroluminescent device, one or more light emitting diodes (LED's), a backlight device, for example, as used for a liquid crystal displays (LCD), or any other light source suitable to illuminate the substrate layer 8 of the optical module 1. Generally, the light source is selected to emit light that passes with minimal attenuation through the substrate layer 8 and the detector layer 10 to illuminate the top surface 15 and the fingertip placed onto the top surface 15 as explained below. In one embodiment, the light is visible and, for example, emitted by an electroluminescent light source.

The electroluminescent light source may be based on inorganic or organic materials. An organic electroluminescent material includes, for example, thin sublimed molecular films such as tris(8-quinolinolato) aluminum (III) commonly known as Alq or light emitting polymers having specialized structures which provide positive and negative charge carriers having high mobilities. The light-

emitting polymers include polyphenylene vinylene (PPV), soluble polythiophene derivatives, and polyanilene which may be applied by known coating techniques such as spin or doctor-blade coating. Further details about organic electroluminescent materials are described in J.C. Sturm et al., "INTEGRATED ORGANIC LIGHT EMITTING DIODE STRUCTURES USING DOPED POLYMERS," Proceedings of SID, 1997, pages F-11-F18.

An inorganic electroluminescent material includes a phosphor material in combination with materials such as zinc sulfide:manganese (ZnS:Mn), zinc silicate (Zn_2SiO_4) or zinc gallate ($ZnGaO_4$). In one embodiment, the phosphor, ZnS:Mn material may be dispersed in an insulating dielectric material such as barium titanate ($BaTiO_3$). Other dielectric materials include yttrium oxide, silicon nitride, and silicon oxy-nitride.

In another embodiment, the light source layer 12 includes an electroluminescent (EL) panel. Such an EL panel is, for example, manufactured by Durel Corporation of Chandler, Arizona, and designated as part number DB5-615B.

Depending on what kind of light source the light source layer 12 includes, the power supply 4 provides either a predetermined voltage or a predetermined current to the light source. For instance, EL panels are voltage-controlled devices. A typical operating voltage for an EL panel ranges approximately between 100 volts and 300 volts. Organic LED's, however, are current-controlled devices. A typical operating current density for an organic LED is in the order of milliamperes per cm^2. Further, the kind of light source determines if the power supply 4 provides an alternating current (AC) or a direct current (DC), or an AC voltage or a DC voltage.

The light source layer 12 includes electrodes that are connected to the power supply 4. In one embodiment, the light source layer 12 has a transparent electrode that faces the substrate layer 8, and a bottom electrode. The transparent electrode is, for example, a transparent polymeric material coated with a transparent electrode composition such as indium tin oxide (ITO) or aluminum doped zinc oxide

(ZnO:Al). In another embodiment, the transparent electrode composition may include transparent aluminum doped zinc oxide (AZO).

Figure 3A shows an embodiment of the optical module 1 in greater detail. In addition, Figure 3A shows a portion of a fingertip 25 placed on top of the surface 15 and having ridges and valleys. The ridges are separated by the valleys and touch the surface 15. The illustrated embodiment of the optical module 1 has the same general structure as the embodiment shown in Figure 2 but shows additional layers. Same elements (layers) have, thus, same reference numerals.

Referring to layers between the top surface 15 and the detector layer 10, a planarization layer 20 covers the detector layer 10 and provides for a planar surface. A planar surface reduces the possibility that undesired residuals remain on the surface of the optical module 1 and allows easy cleaning of the surface. The planarization layer 20 is a transparent dielectric insulator and has a thickness of about 1- 2 μm. In one embodiment, the dielectric insulator is a non-conducting, transparent polymer such as benzocyclobutene (BCB). Other materials for the planarization layer 20 (dielectric insulator) include acrylic or polyimide.

Following the planarization layer 20, a top layer 22 covers the planarization layer 20. The top layer 22 is an electrically conducting material and is in one embodiment connected to ground. As the fingertip 25 is illuminated from within the optical module 1, the top layer 22 is also transparent. In one embodiment, the top layer 22 includes as transparent and conducting material ITO. The top layer 22 has a thickness of about 1000 Å. Although the top layer 22 completely covers the planarization layer 20 in one embodiment, it is contemplated that the top layer 22 may be implemented as a plurality of parallel ITO stripes or as a grid of ITO stripes. An advantage of the conducting top layer 22 is that any static charge the fingertip 25 may carry is discharged from the top surface 15 to ground thereby avoiding electrostatic discharge (ESD) problems.

coating is ITO

& no mention of coating made of alluminim doped zinc oxide

In another embodiment, the transparent and conducting stripes may be implemented so that a finger detection circuit may be fabricated on top of the

planarization layer 20. For example, the finger detection circuit may comprise two ITO electrodes spaced apart from each other. When a fingertip is placed over the these ITO electrodes, a current flows between the ITO electrodes via the fingertip. Further details of detecting the finger are described below with reference to Figure 11.

Referring to layers underneath the light source layer 12, a reflector layer 16 covers a bottom surface of the light source layer 12. In one embodiment, the reflector layer 16 is a thin layer of aluminum which reflects light from the light source layer 12 back into the light source layer 12. Because the reflector layer 16 reflects light back into the light source layer 12, the efficiency of the light source layer 12 is improved and a higher light intensity reaches the top layer 15 and the fingertip 25. The layer of aluminum is conductive and, hence, may serve as an electrode for the light source layer 12. Those skilled in the art will appreciate that other materials that have conductive and reflective properties may be used to form the reflector layer 16. These materials include metals such chromium (Cr), molybdenum (Mo), gold (Au), silver (Ag) and copper (Cu) or alloys including these and other metals.

An insulation layer 18 covers the reflector layer 16 and forms in the illustrated embodiment a bottom surface of the optical module 1. The insulation layer 18 covers the exposed surface of the reflector layer 16 and enhances the mirror effect of the reflector layer 16. In one embodiment, the insulation layer 18 includes a polymer such as polyester. It is contemplated that other insulating materials such as polyethylene may be used.

Figure 3B shows a further embodiment of an optical module 1 which comprises layers and elements already introduced in Figure 3A, same layers and elements have, thus, the same reference numerals. Compared to the embodiment of Figure 3A, the order of the detector layer 10, the light source layer 12, and the substrate layer 8 is changed. That is, in Figure 3B, the light source layer 12 is positioned between the detector layer 10 and the substrate layer 8, whereas in Figure

3A the substrate layer 8 is between the detector layer 10 and the light source layer 12. On top of the detector layer 10, the planarization layer 20 and the top layer 22 are implemented which perform the same functions as described above.

In one embodiment, the light source layer 12 includes a thin-film EL panel and the substrate layer 8 is a glass substrate. Alternatively, the substrate layer 8 may be formed by a layer of plastic-like material. With the substrate layer 8 positioned underneath the light source layer 12, the substrate layer 8 may be transparent or opaque. In addition, the material for the substrate layer 8 may be a rigid or a flexible material.

Figure 4 shows another embodiment of an optical module 1. From the substrate layer 8 upward, the structure of the optical module 1 is as shown in Figure 3A and same elements have the same reference numerals. The illustrated embodiment differs from the embodiment shown in Figure 3A in that a gap 21 exists between the substrate layer 8 and the light source layer 12. The gap 21 may have a width within a wide range, for example, a few microns or several centimeters. In one embodiment, the gap 21 includes a transparent medium (e.g., air, plastic).

The light source layer 12 may be permanently connected to the substrate layer 8 during manufacturing and is an integral part of the optical module 1. In another embodiment, however, the light source layer 12 may be an element separate and independent from the substrate layer 8 and the remaining layers. As a separate element, the user has an additional degree of freedom and may select a particular kind of light source and position it underneath the substrate layer 8. Criteria for selecting the light source include, to name a few, size, thickness, light intensity, power consumption and wavelength spectrum of the emitted light. For instance, if the optical module is implemented within a portable, battery-operated device, the optical module 1 must be as small (thin) as possible and consume as little power as possible. In the same application, however, the light intensity should be as high as possible to sufficiently illuminate the fingertip 25.

The term "optical module 1" as used in this specification is intended to encompass the various embodiments described herein, for example, the embodiments shown in Figures 3A, 3B and the embodiment shown in Figure 4 in which the light source layer 12 may be a separate element. It is contemplated that the optical module 1 may include only the substrate layer 8 and the upper layers 10, 20, 22, without a light source.

Figure 5 illustrates one embodiment of the detector layer 10. The detector layer 10 is implemented on the surface of the substrate layer 8 and covered by the planarization layer 20 and the top layer 22. For illustrative purposes, the fingertip 25 is placed on the surface 15 and two ridges and two valleys are shown. It is contemplated that the Figure 5 is a magnified illustration of the upper layers 10, 20, 22 of the optical module 1 and that the size of the fingertip 25 and the thicknesses of the layers 10, 20, 22 are not to scale.

The detector layer 10 includes spaced-apart photosensitive areas 27 which are distributed over the contact area of the optical module 1. Each photosensitive area 27 is part of a pixel 14 and includes a photodetector 24. The bottom portion (or electrode) of the photosensitive areas 27 are opaque for light originating from the substrate layer 8. In the illustrated embodiment, a single pixel 14 includes the photodetector 24 and a mechanism that stores electrical charge. The pixels 14 are separated by light barriers 28 that extend essentially perpendicular with respect to the substrate layer 8. Between adjacent light barriers 28 a transparent area 19 exists. A light barrier 28 may be formed by a non-conducting opaque material such as a black-matrix material used in liquid-crystal displays (LCDs). In one embodiment, the charge-storing mechanism may be an inherent (parasitic) capacitance of the photodetector 24. In another embodiment, the charge-storing mechanism may be a capacitor 26. For illustrative purposes, the charge-storing mechanism is hereinafter indicated through a conventional symbol for a capacitor (26) and the photodetector 24 is indicated through a conventional symbol for a photodiode. To indicate that the photodetectors 24 and the charge-storing mechanisms 26 function in principle as

individual elements, the photodetectors 24 and the charge-storing mechanisms 26 are illustrated as neighboring elements. It is contemplated that each photodetector 24 is electrically associated with one charge-storing mechanism 26.

The photodetectors 24 are in one embodiment pin photodiodes. In another embodiment, the photodetectors 24 are thin film transistors (TFT) each having terminals referred to as gate, drain and source, wherein the gates are photosensitive areas. The pin photodiodes and the TFT photodetectors, respectively, are manufactured through conventional process technologies typically used to manufacture such photosensitive elements. In case the charge-storing mechanism 26 includes a capacitor, the capacitors (26) are often manufactured during essentially the same manufacturing process as the photodetectors 24. As known in the art, photodetectors are sensitive to incident light. When the intensity of the incident light changes, an internally generated current changes. The current that flows when no light is incident is commonly referred to as a "darkcurrent" and the current that flows when light is incident is referred to as a "photocurrent."

Figure 6 illustrates a magnified section of the detector layer 10 shown in Figure 5. To illustrate the operation of the optical module 1, the detector layer 10 includes photodiodes or phototransistors as photodetectors 24 and capacitors as charge-storing mechanisms 26. A ridge of the fingertip 25 is shown covering one pixel 14. It is contemplated that a ridge of a typical finger may cover about five pixels. Light originating from the light source layer 12 is indicated through dashed lines. Referring to the covered pixel 14, the photodetector 24 and the light barrier 28 are opaque for the light used and light does not pass through the photodetector 24 and the light barrier 28. Light originating from the light source layer 12 passes through the transparent areas 19 between the light barriers 28 and illuminates the fingertip 25. As illustrated, the light illuminates the ridge which is located immediately above the area 19. However, as the ridge covers the photodetector 24 and the area 19 most of the photons are blocked by the ridge and do not reach the photodetector 24. Consequently, only a very small or no photocurrent is generated

and the area above the photodetector 24 is represented as a dark pixel. If a digital signal processing is used, the states "no photocurrent" and "dark pixel" may be represented through a logic state "LOW."

Figure 7 illustrates a magnified section of the detector layer 10 with a valley located above the pixel 14. The detector layer 10 includes also photodiodes or phototransistors as photodetectors 24 and capacitors as charge-storing mechanisms 26. As illustrated, light does not pass through the capacitor 26 and the photodetector 24, but passes through the transparent areas 19 and enters into a cavity formed between the valley and the top surface 15. Light that enters the cavity is randomly reflected at the surface of the cavity. Some of the reflected light is incident upon the photodetector 24 and generates a photocurrent. In this case, the area above the photodetector 24 is represented as a bright pixel. The states "photocurrent" and "bright pixel" may be represented through a logic state "HIGH."

The light source layer 12 functions as a backlight that illuminates the fingertip 25 from within the optical module 1. The backlight illumination allows that the optical module 1 and, hence, the optical sensor system 3 reliably generate a digital image of the fingerprint regardless if the user has a wet, oily or dirty finger. These surface characteristics of the user's finger are usually transparent for the used light and do not influence the path of the light. Light, therefore, enters the cavity and is reflected from the valleys back into the optical module 1.

Figure 8 shows a schematic circuit diagram of a matrix of the photosensitive pixels 14. For ease of illustration, only circuit diagrams of four pixels 14 are shown in greater detail. Each pixel 14 includes one photodetector 24 and one switching element 23 and is connected to a data line L_N, L_{N-1} and an address line L_M, L_{M-1}. It is contemplated that N and M are positive integers. In the illustrated embodiment, the photodetector 24 is a photodiode, for example, a pin photodiode, and the switching element 23 is a switching diode, each having an anode and a cathode. The photodetector 24 is hereinafter referred to as the photodiode 24.

As each pixel 14 has the same structure, one embodiment of the pixel array is described hereinafter with reference to the pixel 14 that is connected to the address line L_M and the data line L_N. The photodiode 24 and the switching diode 23 are connected in series with the cathode of the switching diode 23 connected to the address line L_M and the cathode of the photodiode 24 connected to the data line L_N. The anodes of the diodes 23, 24 are thus connected.

The address lines L_M, L_{M-1} are connected to a power supply 38. The power supply 38 receives a control signal CTRL1 from a central processor (not shown) which controls the operation of the power supply 38. As a function of the control signal CTRL1, the power supply 38 selectively provides an address voltage V_A having predetermined voltage levels of predetermined durations to the address lines L_M, L_{M-1} and, thus, to the cathodes of the individual switching diodes 23.

The data lines L_N, L_{N-1} are connected to amplifiers 32 and convey in operation data voltages V_D to the amplifiers 32. The amplifiers 32 are in one embodiment charge-sensitive amplifiers. Outputs of the amplifiers 32 are connected to a multiplexer 37 having an output 35. The output 35 is connected to a signal processing unit, for example, an analog-to-digital (A/D) converter if the subsequent signal processing is in digital form. The central processor may control the one or more multiplexers.

Figures 8A and 8B show timing diagrams, i.e., DC voltages as a function of the time t, illustrating the operation of the circuit shown in Figure 8. In operation, as shown in Figure 8A, the power supply 38 addresses the address lines L_M periodically with an address voltage V_A. At t = T1, the address voltage V_A changes from a low-voltage level L0, for example, about 0 volts, to a higher-voltage level L1, for example, about 4-5 volts, and returns to the level L0 at t = T2. The period between t = T1 and t = T2 is referred to as "pulse duration." At t = T3, the address voltage V_A changes again from the low-voltage level L0 to the higher-voltage level L1, and returns to the low-voltage level L0 at t = T4.

During the pulse duration, the switching diode 23 is forward biased and a forward-bias current flows through the switching diode 23. The forward-bias current charges an inherent (parasitic) capacitance of the photodiode 24. Following t = T2, i.e., following the falling edge of the address voltage V_A the switching diode 23 and the photodiode 24 are reverse biased.

Between two consecutive pulses, i.e., between t = T2 and t = T3, when the pixel 14 is illuminated, the capacitance of the photodiode 24 is discharged by the photocurrent generated in the photodiode 24. This amount of charge is detected during the following pulse when the photodiode 24 is charged back to its original value, as explained with reference to Figure 8B.

Figure 8B shows the data voltage V_D between t = T1 and t = T4 for two different illuminations I1, I2, with I1 < I2. The higher illumination I2 generates a higher photocurrent than the lower illumination I1. A high photocurrent discharges the capacitance of the photodiode 24 faster than a relative low photocurrent. Hence, at the illumination I2, the data voltage V_D is lower at t = T1 and t = T3 than at the illumination I1. As illustrated, at these instances t = T1 and t = T3 the data voltage V_D is at a level L0, e.g., zero volt, at the illumination I2, and at a level L2, e.g., about 1 volt, at the illumination I1. The amplifiers 32 detect the amount of charge that is necessary to re-charge the capacitance of the photodiode 24.

As the data voltage V_D for the illumination I2 is lower than the data voltage V_D for the illumination I1 at the beginning of the rising edge of the address voltage V_A, a higher amount of charge is necessary to re-charge the capacitance of the photodiode 24 at the illumination I2. The amount necessary for the re-charging is, thus, an indication if a pixel 14 was exposed to light reflected from the valley of the finger 9. As illustrated, the voltage V_D increases within the pulse duration from the level L0 or the level L2, respectively, to a level L3. The level L3 may be at a voltage of about 5 volts.

Figure 9 shows a schematic circuit diagram of a further embodiment of a matrix of the photosensitive pixels 14. For ease of illustration, only circuit diagrams

of three pixels 14 are shown in greater detail. Each pixel 14 includes one photodetector 24, a switching transistor 30, and one capacitor 26. As in Figure 8, each pixel 14 is connected to a data line L_N, L_{N-1} and an address line L_M, L_{M-1}. It is contemplated that N and M are positive integers. In the illustrated embodiment, the photodetector 24 and the switching transistor 30 are thin film field effect transistors having terminals referred to as drain D, gate G and source S. The photodetector 24 (hereinafter referred to as the phototransistor 24) has a photosensitive area that generally exists in an area defined by the gate G.

As each pixel 14 has the same structure, one embodiment of the pixel array is described hereinafter with reference to the pixel 14 that is connected to the address line L_M and the data line L_N. Referring to the phototransistor 24, the drain D and the gate G are both connected to a power line 41 which connects the phototransistor 24 to a voltage supply 43. The source S of the phototransistor 24 is connected to the source S of the switching transistor 30 and a terminal of the capacitor 26 which has a further terminal that is grounded. The drain D of the switching transistor 30 is connected to the data line L_N and the gate G of the switching transistor 30 is connected to the address line L_M.

In use, the voltage supply 43 provides a voltage of about -5 volts to the phototransistor 24. In one embodiment, the voltage supply 43 provides the voltage only during the period the light source 12 is active. In another embodiment, the voltage supply 43 provides the voltage continuously. When the pixel 14 is exposed to light, the (powered) phototransistor 24 generates a photocurrent that charges the capacitor 26 as a function of time and light incident on the phototransistor 24 causes a voltage V_C across the capacitor 26. While the phototransistor 24 is exposed to light, the switching transistor 30 is not conducting and the photocurrent charges the capacitor 26.

The address lines L_M, L_{M-1} are connected to a power supply 38a. The power supply 38a receives a control signal CTRL3 from a central processor (not shown) which controls the operation of the power supply 38a. As a function of the control

signal CTRL3, the power supply 38a selectively provides predetermined voltage levels of a predetermined duration to the address lines L_M, L_{M-1} and, thus, to the gates G of the individual switching transistors 30.

The data lines L_N, L_{N-1} are connected to switches 36. In the illustrated embodiment, each switch 36 has two positions A, B, and receives a control signal CTRL2 that sets the switch 36 to one of the positions A, B. In position A the data line L_N is connected to ground, and in position B the data line L_N is connected to an electrical circuit including an amplifier 45 and a grounded capacitor 34. The circuit has an output 46 for a voltage V_R. It is contemplated that the switch 36 assigned to the data line L_{N-1} has also two positions A, B and is likewise connected to an electrical circuit and ground.

It is contemplated that instead of having one electrical circuit for each data line L_N, L_{N-1}, a multiplexer may be interposed to reduce the number of amplifier circuits. For instance, a multiplexer may be assigned to several data lines L_N, L_{N-1} with an output of the multiplexer connected to the electrical circuit. The central processor may control the one or more multiplexers.

The operation of the circuit is explained with reference to the timing diagrams shown in Figures 10A-10D. Figure 10A shows the address voltage V_A output by the power supply 38a and applied to the address line L_M and the gate G of the switching transistor 30. Figure 10B shows a voltage V_L operating the light source layer 12 of the optical module 1. The voltage V_L indicates periods during which the light source layer 12 emits light and during which the light source layer 12 is dark. Figure 10C shows the voltage V_C across the capacitor 26, and Figure 10D shows the voltage V_R across the capacitor 34.

Referring to Figure 10A, at t = T1, the address voltage V_A changes from a level L0 to a level L1 and returns to the level L0 at t = T2. The period between t = T1 and t = T2 is referred to as "reset cycle." At t = T1, the switch 36 is in the position A connecting the data line L_N to ground. In one embodiment, the address voltage V_A is approximately between 10 volts and 15 volts. The address voltage V_A

which is applied to the gate G turns the switching transistor 30 on and any charge stored on the capacitor 26 flows from the capacitor 26 through the switching transistor 30 (drain-source path), the data line L_N and the switch 36 (position A) to ground. During the reset cycle, the capacitor 34 is also connected so that any charge is discharged to ground.

As shown in Figure 10B, the voltage V_L changes from the level L0 to the level L1 at t = T1 and activates the light source layer 12. At t = T3 (with T3 > T2), the voltage V_L returns to the level L0 deactivating the light source layer 12. Hence, in one embodiment, the light source layer 12 emits light during the reset cycle.

Referring to Figures 10A and 10B, with the electrical circuit and the pixel 14 being reset, the pixel 14 is enabled to detect light. The period between T2 and T3 is referred to as a "detect cycle" and a corresponding operational state of the optical module 1 is referred to as "detect mode." During the detect cycle, the light source layer 12 is active and the switching transistor 30 is turned off. The phototransistor 24 is reverse biased and sensitive to incident light. If no light is incident, the conductivity of a channel existing between the drain D and source S is low and the channel conducts only a minimum current which is commonly referred to as the "dark current."

Assuming light is incident to the gate area of the phototransistor 24, for example, because a valley of the fingerprint is above the pixel 14 (see Figure 7), charge carriers are generated and the conductivity of the channel increases. The generated charge carriers superimpose with the dark current forming a current commonly known as a the "photo current." If a ridge of the fingerprint covers the gate area of the transistor 24, no light is incident and only the dark current flows.

If light is incident, the photocurrent charges the capacitor 26 during the detect cycle and the voltage V_C across the capacitor 26 changes as a function of time as shown in Figure 10C. As the capacitor 26 has been discharged during the reset cycle, the voltage V_C is approximately zero before the charging of the capacitor 26 begins at t = T2. The voltage V_C increases in accordance with a conventional charge

function of a capacitor until the light source layer 12 is turned off at t = T3. The capacitor 26 stores the charge and the voltage V_C remains essentially unchanged after the light source layer 12 has been turned off.

After the detect cycle, the pixel 14 stores information which indicates if a ridge or a valley is present above the pixel 14. It is contemplated that every pixel 14 of the optical module 1 stores information after a detect cycle and the information together represent the relief structure of the fingerprint. In order to make the information available for a subsequent electronic processing, the information needs to be read during a "read cycle" and a corresponding operational state of the optical module 1 is referred to as "read mode."

The read cycle is initiated through applying a positive pulse to the gate G of the switching transistor 30. As shown in Figure 10A, the address voltage V_A changes from level L0 to level L1 at t = T4 and returns to level L0 at t = T5. During the read cycle the switch 36 is in position B connecting the data line L_N to the amplifier 45. Further, the light source layer 12 is deactivated ($V_L = 0$ in Figure 10B) during the read cycle.

The positive address voltage V_A activates the switching transistor 24 as during the reset cycle described above. The activated switching transistor 24 closes a path from the capacitor 26 to the amplifier 45 and a read-out current flows discharging the capacitor 26. The amplifier 45 and the capacitor 34 are connected to form an integrator. The read-out current charges the capacitor 34 causing the voltage V_R. Figure 10D illustrates the voltage V_R as a function of time. The voltage V_R increases during the read cycle, i.e., between t = T4 and t = T5, up to the level L1 and remains essentially constant at this level L1 thereafter. In the illustrated embodiment, the capacitor 34 is discharged at t = T6 and the voltage V_R drops to the level L0.

In one embodiment, the amplifier 45 and the capacitor 34 are part of the driver module 2 (Figure 1). The amplifier 45 and the capacitor 34 are controllable by the controller 6. At the end of the read cycle, the controller 6 "polls" the

capacitor 34 at regular polling instances to determine the voltage V_R at these polling instances. If the voltage V_R has the level L1, the controller 6 interprets this as "valley above pixel 14." If the voltage V_R has the level L0 at a polling instance, the controller 6 interprets this as "ridge above pixel 14." By polling all pixels 14 of the optical module 1 in the same manner, the controller 6 creates the electronic representation of the fingerprint.

Figure 11 shows a further embodiment of an optical image sensor system 3'. The system 3' generally corresponds to the system 3 shown in Figure 1. Same components have therefore the same reference numerals. The optical module 1 is illustrated in a perspective view with a finger 9 placed on the surface 15 of the optical module 1. The optical module 1 includes a contact pad 11 at the surface 15, and a sensor module 7 is connected to the contact pad 11. Like the driver module 2 and the power supply 4, the sensor module 7 is connected to the controller 6.

The sensor module 7 and the contact pad 11 are configured to detect if the finger 9 is placed on the optical module 1. When placed on the optical module 1, the finger 9 closes an electrical loop and a current flows across the finger surface. In one embodiment, the sensor module 7 is a current sensor that detects if the finger 9 is present. In other embodiments, the sensor module 7 may be a voltage sensor that determines a voltage across a resistor, or a sensor that determines the conductivity of the loop.

The contact pad 11 may be implemented in various ways. For instance, the contact pad 11 may be a circular contact element (contact ring) that surrounds the area where the finger 9 is placed, or the contact pad 11 may include several independent pads located in the plane of the surface 15. When the finger 9 is placed, a current flows, for example, between the contact ring, the finger surface, and the grounded surface of the optical module 1. In another embodiment, the contact pad 11 may have several first electrodes and several second electrodes connected to the sensor module 7, wherein the first and second electrodes are interdigited. The finger 9 connects the first and second electrodes and, hence, closes the loop.

Figure 12 is a flow chart illustrating a procedure of operating the optical module 1 of the optical image sensor system 3' shown in Figure 11. The procedure is described with reference to the detector array that includes the switching transistors 30 and the phototransistors 24. It is contemplated that a similar procedure is executed when the detector array includes the switching diodes 23 and the photodiodes 24. The procedure is initialized in step 100 in which the controller 6 may conduct a self-test to determine, among others, if the driver module 2, the power supply 4 and the optical module 1 are properly connected and operable.

Proceeding to steps 104 and 108, the controller 6 determines if the sensor module 7 detects a current that flows between the contact pad 11 and the surface 15 of the optical module 1. In step 108, if the sensor module 7 does not detect a current, the procedure returns along the NO branch to step 104. As long as the sensor module 7 does not detect a current, the controller 6 disables a further execution of the procedure because the finger 9 is not present. However, if the sensor module 7 detects a current, the controller 6 determines that the finger 9 is present and the procedure proceeds along the YES branch to step 112. It is contemplated that the steps 104 and 108 are optional and are omitted in systems, like the optical image sensor system 3 shown in Figure 1, that do not include a sensor module 7.

Proceeding to step 112, the controller 6 resets the optical module 1 to prepare capturing of the fingerprint caused by the finger 9. For instance, the controller 6 applies the positive voltage V_A to the gates G of the switching transistors 30 to reset the capacitors 26 during the reset cycle. It is contemplated that in step 112 and the following steps, the controller 6 operates the switches 36 as described with reference to Figures 10A-10D and no specific reference to the positions A, B of the switches 36 is made hereinafter.

Proceeding to step 116, the controller 6 controls the power supply 4 to activate the light source layer 12. The activated light source layer 12 illuminates the

surface 15 of the optical module 1. As shown in Figures 10A, 10B, the light source layer 12 is activated at the beginning of the reset cycle (t = T1).

Proceeding to step 120, the controller 6 operates the driver module 2 to apply a positive voltage V_D (level L1) to the data lines L_N, L_{N-1} and thus to the drains D of the switching transistors 30. During this detect cycle, the phototransistors 24 which are covered by ridges do not generate photocurrents and the capacitors 26 are not charged. However, those phototransistors 24, which are not covered by ridges, generate photocurrents that charge the capacitors 26. Figure 10D illustrates the charging of the capacitors 26 as a function of time.

Proceeding to step 124, the controller 6 operates the driver module 2 to read the information stored on the capacitors 26. With the voltages V_A and V_L and switches 36 properly set, conductive paths exist between the capacitors 26 and the amplifiers 32 and the capacitors 34. Those capacitors 26, which have been charged by the photocurrents, are sources for discharge currents that the amplifiers 32 and the capacitors 34 integrate. If the voltage V_R of a capacitor 34 is at the level L1, a valley was placed over the pixel 14 and, correspondingly, if the voltage V_R is at the level L0, a ridge covered the pixel 14.

During the read cycle, the controller 6 determines the values of the voltages V_R of the capacitors 34. In their entirety, these values represent a digital representation of the fingerprint. The controller 6 can evaluate the representation and determine the quality of the representation, for example, if the fingerprint image is too bright or too dark, or if the exposure time needs to be increased or decreased. In any case, the controller 6 may adjust the intensity of the light emitted by the light source layer 12 by controlling the voltage and/or the duration of the voltage supplied to the light source layer 12.

Because of this adjustment process, the steps 112-124 may be repeated as indicated in step 128. In one embodiment, the procedure returns along the YES branch to step 112 three times in order to generate four representations of the fingerprint images. For instance, the representations are generated at a rate of four

representations per second. When the fourth representation is generated the procedure proceeds along the NO branch to step 132.

In step 132, the final representation of the fingerprint image is captured and stored in a storage device. The storage device may be accessed by a matching unit, which compares the captured representation of the present fingerprint with a stored fingerprint of the owner. The matching unit may be located within the controller 6 or within the host system. The procedure ends at step 136.

Figure 13 shows a blockdiagram of a driver module 2 which may be configured for use with the electrical circuits shown in Figure 8 and Figure 9. The driver module 2 is associated with the N address lines L_N, L_{N-1} (rows) and M data lines L_M, L_{M-1} (columns) of the optical module 1. In the illustrated embodiment, the driver module 2 includes components which are already shown in Figure 8 and Figure 9. That is, for example, a multiplexer 8 corresponds to the multiplexer 37 of Figure 8, and an input amplifier module 140 includes the amplifiers 32 shown in Figure 8.

The input amplifier module 140 has N inputs and N amplifiers to connect to the data lines L_N, L_{N-1}. The N amplifiers of the input amplifier module 140 operate as charge sense amplifiers to determine the charge necessary to re-charge the capacitance of the photodiode 24 (Figure 8B). The input amplifier module 140 has N outputs which are connected to inputs of the multiplexer 142. The multiplexer 142 has an output 143 which is connected to an input of an analog-to-digital (A/D) converter 144. An output of the A/D converter 144 is connected to a control logic 146.

The control logic 146 is connected to an interface 148 which has an output 149 for a signal DATA and which is connected to the controller 6. The control logic 146 is further directly connected to the controller 6 to receive a control signal CTRL that the control logic 146 uses to generate individual control signals. Control lines 154, 156, 158 connect the control logic 146 to the input amplifier module 140, the multiplexer 142, and the A/D converter 144, respectively. For instance, the

individual control signals include a control signal to set an amplification factor of the input amplifier module 140, and timing control signals to clock the multiplexer 142 and the A/D converter 144.

The driver module 2 further includes a column driver 150 and a row driver 152. The column driver 150 may be disabled when used in combination with the circuit of Figure 8. A control line 160 connects the column driver 150 and the control logic 146, and a control line 162 connects the row driver 152 and the control logic 146. In one embodiment, the column driver 150 has N outputs connected to the switches 36, and generates N control signals CTRL2, one for each switch 36, to operate the switches 36 between the positions A, B.

In the illustrated embodiment, the row driver 152 has an output which is connected to the power supply 38, 38a. The output provides the control signal CTRL1, CTRL2 which controls the power supply 38, 38a to drive the address lines L_M with the voltage V_A. It is contemplated that in another embodiment the row driver 152 may have M outputs to directly drive each address line L_M. In this case, the row driver 152 includes a power supply corresponding to the power supply 38, 38a.

The driver module 2 is in one embodiment implemented as an application specific integrated circuit (ASIC), for example, in CMOS technology. Those skilled in the art will appreciate that the driver module 2 may also be implemented, for example, in hybrid technology using discrete components. Further, those skilled in the art will appreciate that in other embodiments the structure of the illustrated driver module 2 may be modified although the general function of the driver module 2 is maintained.

Figure 14 shows another embodiment of an optical module 1'. The fingertip 25 is placed on the surface 15, wherein a ridge covers a pixel 14a and a valley is located above a neighboring pixel 14b. The pixels 14a, 14b are representatives of the pixels 14 of the optical module 1', which have the same structure as the pixels

14a, 14b. The general structure of the pixels 14 is described with reference to the pixel 14a.

The optical module 1' has a multiple layer structure. In the illustrated embodiment, four layers 8', 10', 20, 22 are shown, wherein the layers 20, 22 are the planarization layer 20 and top layer 22, respectively, described with reference to Figure 3. The planarization layer 20 covers an active layer 10', which is implemented on a substrate layer 8'. Within the active layer 10', the pixels 14, 14a, 14b are implemented. The active layer 10' also includes conductor lines (not shown) to electrically connect the pixels 14, 14a, 14b, for example, to the driver module 2.

The pixel 14a includes a light source 50 and a photodetector 24' which are both implemented in the active layer 10'. The photodetector 24' is in one embodiment a pin photodiode, and the light source 50 is a light emitting diode (LED). The photodetector 24' and the light source 50 are indicated through conventional symbols, respectively. In another embodiment, the photodetector 24 is a photodiode or a phototransistor (e.g., a TFT). A light barrier 52 separates the photodetector 24' and the light source 50 to avoid that light is directly incident on the photodetector 24'. The light barrier 52 is indicated through a dashed line between the symbols for the photodetector 24' and the light source 50. Those skilled in the art will appreciate that each pixel 14 is optically isolated from neighboring pixels 14 to avoid that light from the light source 50 is directly incident on the photodetector 24' of a neighboring pixel 14.

It is contemplated that the light barrier 52 may be implemented in various ways. For instance, in one embodiment, the light barrier 52 may be an opaque, wall-like barrier that may extend in vertical direction beyond the planes of the photodetector 24' and the light source 50. In another embodiment, the light source 50 or the photodetector 24' may be positioned within cavities that have openings facing the planarization layer 20. In yet another embodiment, both the photodetector 24' and the light source 50 may be positioned within cavities.

The substrate layer 8' includes a material selected to allow the implementation of the active layer 10' through conventional high temperature, chemical deposition processes, and may be a transparent or opaque material. In one embodiment, the substrate layer 8' is a glass substrate onto which the active layer 10' is grown. In other embodiments, the substrate layer 8' may be a semiconductor substrate such as a silicon or gallium arsenide substrate, or a temperature resistant polymer material.

In Figure 14, the valley of the fingertip 25 is above the pixel 14b and the ridge covers the pixel 14a. In operation, the light source 50 of the pixel 14b emits light that passes through the layers 20, 22 and is reflected on the inclined surfaces of the valley. The reflected light is incident on the photodetector 24' which generates a photocurrent, as described above. The photocurrent indicates that a valley was located above the pixel 14b. The light source 50 of the pixel 14a also emits light that passes through the layers 20, 22, but substantially no light is incident on the photodetector 24' because the pixel 14a is covered by the ridge. As a consequence, the photodetector 24' does not generate a photocurrent. The substantially unchanged dark current indicates that a ridge covered the pixel 14a.

Focusing on a particular embodiment of the detector layer 10, Figure 15 shows an enlarged view of a section of the pixel 14. As in the previous embodiments, the pixel 14 includes, from top to bottom, the top layer 22, the planarization layer 20, the detector layer 10, the substrate layer 8, the light source layer 12, the reflector layer 16, and the insulation layer 18. As in Figure 4, the gap 21 separates the light source layer 12 and the substrate layer 8. In another embodiment, the light source layer 12 and the substrate layer 8 are in direct contact, for example, as shown in Figure 3.

The detector layer 10 includes a photodetector 24' which is in the illustrated embodiment a photodiode. It is contemplated that the pixel 14 further includes the switching diode 23 which is not shown in the illustrated section of the pixel 14. The photodiode 24' is a pin photodiode which comprises a photoactive p-layer 24a, an

intrinsic (i)-layer 24b and an n-layer 24c. The photodiode 24' is implemented above an electrode 27 through a conventional process for pin photodiodes. The n-layer 24c is formed by a layer of amorphous silicon (a-Si:H) doped to be of n-type silicon, and the p-layer 24a is formed by a layer of amorphous silicon doped to be of p-type silicon. Between the p- and n-layers 24a, 24c, a layer of undoped amorphous silicon forms the i-layer 24b. The p-layer 24a can be covered by a layer of transparent and conducting ITO (not shown) which is in contact with an electrode 29 indicated on top of the p-layer 24a.

The electrodes 27, 29 and bus lines 31a, 31b are, for example, thin layers of chromium. It is contemplated that other conducting materials, such as molybdenum (Mo) or tungsten (W), may be used to form the electrodes 27, 29 and the bus lines 31a, 31b. In one embodiment, the bus lines 31a are part of the lines L_N, L_{N-1} and the bus lines 31b are part of the lines L_M, L_{M-1}. The bus lines 31b are implemented on top of the bus lines 31a and separated through a passivation layer 35. The passivation layer 35, thus, covers the bus lines 31a and the pin diode 24'.

The p-layer 24a faces the top surface 15 through which light re-enters the optical module 1 when the walls of a valley reflect the light. The photodiode 24' ideally does not receive light reflected from a ridge located above the pixel 14. The pixel 14 includes a light barrier 33 that surrounds the photodiode 24' avoiding that extraneous light is incident onto the photodiode 24' covered by the area of the ridge. Without the light barrier 33, sidewalls of the photodiode 24' would be exposed to backlight illumination. Therefore, photocurrent would be generated by absorbing light incident via the sidewall. The increase in the photocurrent would increase the noise level and hence reduce the contrast ratio of the fingerprint image. In one embodiment, the light barrier 33 has a hollow, elongate body of an opaque material. The opaque material may be an organic resin or any nonconducting material.

The light barrier 33 is formed through a multiple-step process. When the photodiode 24' has been implemented, in a first step, the opaque material is applied through, for example, spin coating so that the opaque material covers the photodiode

24', the bus lines 31, and the remaining areas of the pixel 14. In a second step, a mask is applied and the shape and location of the light barrier 33 is defined by means of a photo-lithography process. A third step is a dry-etching process which removes undesired opaque material thereby forming the light barrier 33. The third step may be simplified without using a dry-etching process if a photo-definable opaque material is used.

After the photodiode 24' and the light barrier 33 are implemented, the transparent planarization layer 20 is applied. The planarization layer 20 may completely cover a top surface of the light barrier 33 as illustrated. In another embodiment, however, the top surface of the light barrier 33 may be in the same plane as the top surface of the planarization layer 20 and covered by the top layer 22.

The light barrier 33 prohibits that scattered light is incident on the photodiode 24' and, thus, allows only reflected light to enter the photodiode 24'. The pixel 14 provides for an improved contrast because the difference in intensities between "dark" and "bright" is greater. "Dark" refers to a situation in which the pixel 14 is covered by a ridge, and "bright" refers to a situation in which a valley is located above the pixel and the walls of the valley reflect light.

Those skilled in the art will appreciate that in another embodiment the light barrier 33 and a TFT transistor may be combined. As in the above example, the light barrier 33 protects the TFT transistor from scattered or lateral incident light. Further, those skilled in the art will appreciate that the light barrier 33 may also be combined with the embodiment shown in Figure 14 in which the photodetector 24' and the light source 50 of a pixel 14 lay in the same plane.

Figure 15A shows a further enlarged view of a section of the pixel 14. As in the previous embodiments, the pixel 14 includes, from top to bottom, the top layer 22, the planarization layer 20, the detector layer 10, the substrate layer 8, and the light source layer 12. In another embodiment, the light source layer 12 and the substrate layer 8 may be separated through a gap, for example, as shown in Figure 4.

The detector layer 10 includes a photodetector 24'' which is a pin photodiode which comprises a photoactive p-layer 24d, an intrinsic (i)-layer 24e and an n-layer 24f. The photodiode 24'' is implemented above a chromium (Cr) electrode 27a through a conventional process for pin photodiodes. The n-layer 24f is formed by a layer of amorphous silicon (a-Si:H) doped to be of n-type silicon, and the p-layer 24d is formed by a layer of amorphous silicon doped to be of p-type silicon. Between the p- and n-layers 24a, 24c, a layer of undoped amorphous silicon forms the i-layer 24e. The p-layer 24d is covered by a layer 27b of transparent conducting ITO which is in contact with an electrode 29a indicated on top of the p-layer 24d.

The electrodes 27a, 29a and bus lines 31c, 31d are, for example, thin layers of chromium or a combination of chromium and aluminum. It is contemplated that other conducting materials, such as Mo or W, may be used to form the electrodes 27a, 29a and the bus lines 31c, 31d. In one embodiment, the bus lines 31c are part of the data lines L_N, L_{N-1} and the bus lines 31d are part of the address lines L_M, L_{M-1}. The bus lines 31d and the bus lines 31c are separated through a passivation layer 35a.

In the illustrated embodiment, the switching diode 23 is also a pin photodetector and has generally the same structure as the pin photodiode 24' of Figure 15. The light barrier 33 is implemented as described above. In addition, the light barrier 33 covers the switching diode 23.

Figure 16 shows a top view of the section of the pixel 14 shown in Figure 15A, including the switching diode 23, to illustrate a layout of the pixel 14. As illustrated, the photodetector 24' has a rectangular shape and is connected to the bus lines 31a (columns/data) and the bus lines 31b (rows/address). The elongate light barrier 33 has a rectangular cross-section and covers the switching diode 23 and a part of the photodetector 24'. The light barrier 33 has a quadratic area 39 which does not cover the photodetector 24' and, thus, allows light to be incident on the photodetector 24'.

In the illustrated embodiment, the cross-section of the area 39 corresponds to the cross-section of the light barrier 33. However, in other embodiment, the cross-section of the area 39 may be different from the cross-section of the light barrier 33, for example, circular.

Figure 17 shows an embodiment of an optical module 200 with the finger 9 placed onto a contact surface 201. As in the previous embodiments, the optical module 200 is configured so that the valleys of the finger 9 reflect light, which originates from within the optical module 200, back into the optical module 200.

The optical module 200 comprises a substrate 210 and a light emitting layer 202. In the illustrated embodiment, the light emitting layer 202 includes a plurality of discrete light sources 204. The substrate 210 is transparent for light emitted by the light sources 204. A surface 212 of the substrate 210 faces the finger 9 and receives the light sources 204. The layer 202 covers the light sources 204 as a protective coating and provides that the contact surface 201 is planar. In one embodiment, the substrate 210 has a thickness of about 0.5-1.5 mm, and the layer 202 has a thickness of about 1 μm.

The optical module 200 comprises further an optical lens 206 and an opto-electronic (O/E) converter 208. The optical lens 206 is located between the substrate 210 and the O/E converter 208 along an axis 221 that is perpendicular to a surface 214 that faces the optical lens 206. In Figure 17, rays 218 illustrate light which is reflected by the valleys and incident on the optical lens 206, rays 220 illustrate light which is passed through the lens 206 and incident on the O/E converter 208.

In one embodiment, the light sources 204 are arranged in spread relationships as a pixelized array of individual light emitting diodes (LED). Each LED is connected to a power supply via a pair of electrodes. In operation, each LED emits a cone-shaped beam of light having a predetermined aperture. The cone-shaped beam of light illuminates an area of the finger 9. The area directly underneath the LED, or the substrate of the LED itself, is opaque so that no light is emitted directly into the substrate 210. The electrodes of the LED's are transparent for light emitted by the

LED's. In one embodiment, the electrodes are formed by ITO. Figure 17A shows an embodiment of a light source 204 for a pixel for the optical module 200.

In another embodiment, the light emitting layer 202 includes a single sheet of thin film electroluminescent (EL) material that forms a patterned EL light source. Figures 18 and 19 show embodiments of EL light sources. The EL light source is connected to a power supply via a first electrode that faces the finger 9 and a second electrode on top of the substrate 210. The first electrode is transparent for light emitted by the EL light source to allow undisturbed illumination of the finger 9. The area between the EL light source and the substrate 210 has an opaque pattern that prevents light emitted by the EL light source from directly illuminating the lens 206, while allowing light reflected from the finger 9 reach the lens 206. The opaqueness may be achieved by an opaque second electrode or an opaque coating.

In one embodiment, the optical lens 206 has a distance from the light sources 204 of about 40 mm, and a distance of about 8 mm from the O/E detector 208. In operation, the light sources 204 illuminate the finger 9. The combination of covered ridges and light reflected by the valleys form an image of the fingerprint. The lens 206 projects the image onto the O/E detector 208 which converts the reduced image of the fingerprint into an electronic representation of the fingerprint.

The O/E detector 208 has an output 216 for a signal that corresponds to the electronic representation and that is available for a subsequent signal processing. The O/E detector 208 may be a CMOS imager, an array of photodiodes, a device that includes an array of charge coupled devices (CCD), or any other device that converts the image of the fingerprint into an electronic representation.

Figure 17A shows an embodiment of a light source 204 of a pixel of the optical module 200. The pixel includes, from top to bottom, a top layer 240, the layer 202 that includes a planarization layer 254 and the light source 204, and the substrate 210. In the illustrated embodiment, the light source 204 and the subsequent layers 254, 240 are implemented on top of the substrate 210 which may be a glass substrate.

The light source 204 includes, from the substrate 210 upwards, the following layers: an electrode layer 244 which may include a chromium or aluminum, a semiconductor layer 246 which may include a-SiN_xO_y or a-SiN_x, a light emitting phosphor layer 248, a semiconductor layer 250 which may include a-SiN_xO_y or a-SiN_x, so that the phosphor layer 248 is embedded between the semiconductor layers 246 and 250 within an light emitting area, and on top of the semiconductor layer 250 an electrode layer 252 which may include indium tin oxide (ITO).

The pixel includes a light barrier 242 that surrounds the light source 204. The light barrier 242 prohibits that emitted light propagates in horizontal direction. In one embodiment, the light barrier 242 has a hollow, elongate body of an opaque material. The opaque material may be an organic resin or any nonconducting material. In Figure 17A, the light barrier 242 is shown as extending left and right of the light source 204 between the substrate 210 and the top layer 240. The light barrier 242 is formed through a multiple-step process as described above.

Figure 18 shows a section of a first embodiment of an EL light source within the layer 202. The EL light source includes a light emitting area 224 and isolated areas 226 which do not emit light. In the illustrated embodiment, the areas 226 are squares through which the reflected light from the finger can pass through. For instance, neighboring areas 226 have a distance of about 50 μm, center to center. It is contemplated that in other embodiments, the areas 226 may have, for example, oval or circular shapes.

Figure 19 shows a section of a second embodiment of an EL light source 202' which forms the layer 202. The EL light source 202' includes isolated light emitting areas 230 and an area 228 that does not emit light. In the illustrated embodiment, the light emitting areas 230 are squares. The EL light source 202' may be implemented similar to the EL light source 202, however, with a complementary structure. That is, the area 228, which is similarly shaped as the area 224 in Figure 18, does not emit light, whereas the area 224 emits light.

Figure 20 shows an embodiment of an optical module 300 which is a modified version of the optical module 200 shown in Figure 17. In Figures 17 and 20 same elements have, thus, the same reference numerals. An axis 304 is perpendicular to the surface 214 and an axis 306 is perpendicular to a convex surface 308 of the lens 206. The axis 304, 306 are perpendicular to each other. The optical module 300 includes a reflector 302, which is positioned in a plane between the substrate 210 and the lens 206 where the axis 304, 306 intersect.

The reflector 302 is in one embodiment a planar mirror that diverts the light reflected by the valleys of the finger 9 by about 90 degrees so that the light is incident on the lens 206. The reflector 302 has a rectangular reflector surface which is sized to project the complete image of the fingerprint onto the lens 206. In one embodiment, the area of the reflector surface is about half the size of the surface 214. Because the reflector 302 diverts the light, the optical module 300 is thinner than the optical module 200. In one embodiment, the optical module 300 is approximately half as thick as the optical module 200.

Figure 21 shows a further embodiment of an optical module 500 onto which the finger 9 is placed. The optical module 500 includes a detector layer 502 and the layer 202 that includes the light sources 204 as explained above. Between the layer 202 and the detector layer 502, the optical module 500 includes a planarization/isolation layer 504 which has a thickness of a few microns, for example, about 4 μm. As in the previous embodiments, the valleys of the finger 9 reflect light emitted from within the layer 202 back into the optical module 500 where the detector layer 502 receives the reflected light. In one embodiment, the detector layer 502 is an array of pin photodiodes, for example, as shown in Figure 9 and explained above.

Figure 22 shows an embodiment of an optical module 400 that comprises a fiber optic bundle 402. The fiber optic bundle 402 has a surface 404 onto which the finger 9 is placed, an input branch 408 with an input surface 410, and an output branch 406 with an output surface 412. The input surface 410 receives light which

the input branch 408 guides to the surface 404 in order to illuminate the finger 9. As in the previous embodiments, the valleys of the finger 9 reflect light back into the fiber optic bundle 402. Within the fiber optic bundle 402 the output branch 406 guides the reflected light to the output surface 412 where the light is incident on a O/E detector 414 which is connectable to a signal processing device.

The fiber optic bundle 402 includes a plurality of individual optical fibers. In one embodiment, about half of the optical fibers form the input branch 408 and the remainder of the optical fibers form the output branch 406. The optical fibers of the input branch 408 are referred to as "transmitter fibers" and the optical fibers of the output branch 406 are referred to as "receiver fibers." In proximity of the surface 404, the optical fibers are densely packed and arranged in a rectangular array of pixels having m rows and n columns and forming a planar contact area. In one embodiment, the contact area has a size of about 2.5 cm x 2.5 cm (1 inch x 1 inch) to receive the finger 9. A typical outer diameter (without protective plastic coating) of an optical fiber is about 100 μm with a light guiding core of about 10 μm.

In one embodiment, each pixel includes an end section of a transmitter fiber and an end section of a receiver fiber. For instance, the optical fibers may be arranged so that in each row and each column the transmitter fibers alternate with the receiver fibers. Further, the arrangement may be that a transmitter fiber directly neighbors only a receiver fiber, but not a transmitter fiber.

Figure 19 shows four array locations $R_{1,1}$, $R_{1,n}$, $R_{m,1}$, $R_{m,n}$, each including a receiver fiber. The array locations $R_{1,1}$, $R_{1,n}$, $R_{m,1}$, $R_{m,n}$ are shown at the surface 404 and at the surface 412 to indicate that the arrangement of the receiver fibers does not change between the surfaces 404 and 412. That is, the receiver fibers that are exposed at the surfaces 404, 412 have a fixed, coherent relationship, and thus comprise a coherent fiber bundle. The coherent relationship ensures that light exiting, for example, at the array location $R_{1,1}$ of the output surface 412 was input at the array location $R_{1,1}$ of the surface 404.

In operation, a light source 416 emits light which may be monochromatic or "white" light. The light source 416, thus, may be selected from a variety of different light sources, for example, halogen lamps, regular light bulbs, neon tubes, or even day light to name a few. The light illuminates the finger 9 via the transmitter fibers and, with respect to the finger 9, every transmitter fiber is a miniature light source (within a pixel) that illuminates a small area of the finger 9. If a valley is above a miniature light source, the valley reflects light back to the surface 404 where the reflected light may enter at least one receiving fiber. However, if a ridge covers a pixel, no light is reflected from the transmitter fiber to the receiving fiber and the receiving fiber remains "dark." As explained above, the entirety of the illuminated and dark receiving fibers forms the image of the fingerprint which is detected by the O/E converter 414.

The optical image system 3 shown in Figure 1 and the various embodiments of the optical module 1, 200, 300, 400 may be adapted to a variety of applications. For instance, when implemented to function as a touch screen, the optical image system 3 may detect, which area, i.e., what symbol, the user touched. Further, the optical image system 3 may trace the movement of the user's finger or pen when the user "writes" onto the surface. During the movement, subsequent pixels 14 are covered, the finger or pen reflect light, and the pixels 14 subsequently output photocurrents that allow tracing the movement. In addition, the optical image system 3 may be configured to determine the shape of an object placed on top of the optical module 1. A processor may match the determined shape with a number of stored shapes. In another embodiment, the processor may "measure" the area of the object, for example by counting the number of covered pixels 14 when the area of an individual pixel 14 is known.

While the above detailed description has shown, described and identified several novel features of the invention as applied to a preferred embodiment, it will be understood that various omissions, substitutions and changes in the form and details of the described embodiments may be made by those skilled in the art without departing

from the spirit of the invention. Accordingly, the scope of the invention should not be limited to the foregoing discussion, but should be defined by the appended claims.